N65-83268#

PREPRINT: Subject to revision. Permission to publish this paper, in full or in part, after its presentation and with credit to the author and the Society may be obtained upon request. The Society is not responsible for statements or opinions advanced in papers or discussions at its Meetings.

105

STABILITY AND CONTROL OF THE AERIAL JEEP

By

M. O. McKINNEY

Aeronautical Research Engineer
NASA Langley Research Center

STATEMENT FOR OFFICIALS OF SAE

We did not learn until after the papers for this session had been printed for distribution that the word "Jeep" is the registered trademark of Willys Motors, Inc., and that word should not have been used in these papers for that reason. With this correction and recognition in mind, the distribution of the papers will be continued.

SAE ANNUAL MEETING
Sheraton-Cadillac & Statler Hotels
Detroit, Michigan
January 12-16, 1959

Written discussion of this paper will be accepted by SAE until Feb. 16, 1959. Three double-spaced copies are appreciated.

SOCIETY of AUTOMOTIVE ENGINEERS, Inc., 485 Lexington Avenue, New York 17, N. Y.

STABILITY AND CONTROL OF THE AERIAL JEEP

* * * * * * * * * *

SUMMARY

This paper presents a discussion of some of the stability and control problems of the aerial jeep based on experimental and analytical research by the NASA. The work has indicated that the aerial jeep is feasible from a stability and control standpoint in that it can be made to fly satisfactorily in both hovering and forward flight but that a certain degree of artificial stabilization may be required. A great deal of research and development on a number of detailed problems is required, however, before this desirable end can be achieved in practice.

* * * * * * * * * *

INTRODUCTION

The purpose of this paper is to discuss some of the fundamental stability and control problems of the aerial jeep as it is currently visualized. Several examples of such aerial jeep configurations are shown in Fig. 1. Basically they consist of a body for the engine, pilot, and cargo supported by two or more propellers which are fixed with respect to airframe so that the plane of rotation is horizontal for hovering flight. The propellers might be either shrouded or unshrouded.

FUNDAMENTAL CHARACTERISTICS OF PROPELLERS

The sketches in Fig. 2 illustrate some of the fundamental characteristics of propellers which can be used to explain most of the main stability characteristics of the aerial jeep. This figure shows an unshrouded propeller and a shrouded propeller in a cross flow. The unshrouded propeller deflects the flow downward through some modest angle which gives rise to lift and drag forces. The forward part of the propeller disk imparts a downwash through the rearward part of the disk that reduces the thrust of the rearward part of the disk and results in a thrust distribution like that shown in Fig. 2, which in turn results in a nose-up pitching moment. The shrouded propeller deflects the flow downward through a larger angle so that it leaves the shroud parallel to the propeller shaft axis. This large angular deflection of the flow causes a drag which is much larger than that of the unshrouded propeller. The cross flow increases the flow over the leading lip of the shroud and reduces the flow over the rearward lip of the shroud, thereby causing the unequal pressure distribution on the shroud indicated in Fig. 2. It also, very likely, causes an unsymmetrical thrust distribution on the propeller like that shown in the figure. The effect of the shroud pressure distribution and propeller thrust distribution on pitching moment are additive and result in a nose-up pitching moment larger than that of the unshrouded propeller.

STABILITY IN HOVERING

The principal stability characteristic of the aerial jeep in hovering flight is an unstable oscillation in pitch and roll. An example of this oscillation is shown in Fig. 3 which presents a time history of such an oscillation for a flying model. This flight record shows that the oscillation involves both bank and lateral displacement. The oscillation results from the pitching (or rolling) moment shown in Fig. 2. For example, if the machine starts to move forward, it develops a nose-up pitching moment which is statically stabilizing since it causes the machine to pitch nose up and tilt the thrust vector backward to provide a force to stop the translational velocity. The damping in pitch is too low, however, so the machine overcorrects and develops an even larger velocity in the other direction thereby building up an unstable oscillation.

If two propeller are used, for example in a tandem arrangement, the pitching moment caused by a forward velocity is even greater, as illustrated in Fig. 4, because of the downwash of the leading propeller on the following one which reduces the thrust of the following propeller. The damping of the angular velocity is much greater, however, because a relatively small angular velocity can cause a fairly large upward and downward velocity of the propellers which causes a variation in thrust to oppose the pitching velocity. For example, if a tandem propeller machine develops a nose-up pitching velocity, the forward propeller moves upward which increases its inflow velocity and reduces its thrust while the rearward propeller moves downward which reduces its inflow velocity and increases its thrust. These changes in thrust produce a damping moment opposing the angular velocity. There is a corresponding upward and downward motion of the forward and rearward parts of the propeller which results in similar changes in thrust and a damping moment. The damping in pitch of two propellers spaced out in tandem, however, is much more than the damping in roll of the same two propellers about the long axis of the machine because of the greater moment arms involved. This increase in damping has a much greater effect on the oscillation than the increase in pitching moment due to forward velocity so that the pitching oscillation of a tandem propeller machine is much less unstable than the rolling oscillation.

The two-shroud and four-shroud models shown in Figs. 5 and 6 have been flown at the Langley Research Center of the NASA using the remote-control trailing-cable technique to get some preliminary indications of the stability and control characteristics of multiple-shroud aerial jeeps. They are not scale models of any particular aerial jeep design, but are generally representatives of two principal types. With a width of 3 feet, lengths of 8 feet and 5 feet, and weight of 75 pounds, the models represent approximately 0.3-scale models of some of the proposed aerial jeeps. These models were laid out to have the same width, representing aerial jeeps that could be carried in a cargo airplane of a given width, and had the same space between the shrouds to represent the same space for engine, pilot, and cargo. This procedure, which was thought to represent a likely design procedure, resulted in a greater overall length for the two-shroud model.

Flight tests of the two-shroud model showed that the rolling oscillation (oscillation about the long axis) was very unstable and of a relatively high frequency, because of the low rolling moment of inertia, while the pitching oscillation was only slightly unstable and had a relatively long period because of the high pitching moment of inertia. Flight tests of the four-shroud model showed that the rolling oscillation had about the same degree of instability as that of the two-shroud model. Apparently, two distinct propellers having the same total width and same total thrust as a single larger propeller did not cause any significant difference in damping. The pitching oscillation of the four-shroud model was much more unstable than that of the 2-shroud model and was, in fact, not a great deal more stable than the rolling oscillation. This characteristic probably results from differences in damping which varies as the square of the length (or width). The four-shroud model had considerably less damping in pitch because it was shorter than the two-shroud model, and had only a little more damping in pitch than in roll because it was only a little longer than it was wide.

In the tests of the flying models it was found that the pitching and rolling oscillations could be made completely stable by the use of artificial damping in pitch and roll. The model was equipped with a rate gyroscope to detect the angular velocity and provide a signal to the control actuator to move the controls to oppose the angular velocity. The effect of such a damper on the rolling oscillation (which was the more unstable of the oscillations) is shown for the four-shroud model by the time histories in Fig. 7. In neither of these records did the human pilot apply any roll control. The records show that the model was very unstable without artificial damping; whereas, with the damper operating the model would fly for an indefinite period of time without developing an unstable oscillation even though it was moving about continuously in the somewhat rough recirculating air in the flight test enclosure.

Stability in yaw in hovering should be no problem with the aerial jeep in still air. Such a machine would develop no yawing moments from translational velocity because of its geometric symmetry, and would probably have some damping of yawing velocity. It would therefore have no tendency either to oscillate or diverge. The yaw behavior of an aerial jeep in gusty air or when flying near an obstruction might be erratic, however, if the gusts or recirculating flow off the obstacle were unsymmetrical. For example, if a side gust blew harder on one end of the vehicle than the other there would be a considerable difference in the side-force (particularly of a shrouded propeller as indicated in Fig. 2) which would produce a sizable yawing moment. This effect has been noted with the two flying models when flying in a large building. At first when the air was still the model was very steady in yaw, but later as the slipstream began to recirculate in the building the random nature of the recirculation caused the model to become erratic and unsteady in yaw.

All of these unsatisfactory stability characteristics (unstable pitching and roll oscillations, and erratic response in yaw to gusts) would be expected to be less severe for an aerial jeep with unshrouded propellers than shrouded propellers because of the lesser pitching moment and drag resulting from translational velocity. At the present time, however, the NASA has no flight experience or detailed dynamic stability analysis to support this conjecture.

CONTROL IN HOVERING

Control of a four-propeller configuration can be fairly simple and straightforward. Pitch and roll control can be obtained by varying the thrust of propellers at opposite ends or opposite sides of the machine; and yaw control can be obtained by means of a simple control vane beneath the propellers or by varying the total pitch of the various propellers to produce a net change in torque. In this latter case it is necessary to have oppositely rotating propellers with diagonally opposite propellers having the same direction of rotation in order that the pitch of one pair of diagonally opposite propellers may be increased and that of the other pair decreased to produce a change in net torque without producing a ptiching or rolling moment.

Control of a two-propeller configuration, however, is not so straightforward. Varying the total pitch of the two propellers will provide control about one axis (for example, pitch control for a tandem configuration), but will give a yawing moment if oppositely rotating propellers are used. This yawing moment would probably have to be cancelled out by some means such as a mechanical interconnection that would provide some yaw control together with the pitch control. Yaw control could be accomplished simply by means of a control vane beneath the propellers, but could not be accomplished by varying the propeller pitch since the required change would also give a pitching moment for the case of oppositely rotating propellers, or a change in thrust for the case of propellers rotating in the same direction.

A suitable moment about the long axis of a two-propeller machine (that is, a rolling moment for a tandem machine) can be produced by cyclic variation of the blade angle of nonarticulated propellers so that the blades are at a higher angle and produce more thrust on one side of the disk than the other. A similar moment can be produced by a spoiler or drag type device which spoils the thrust or causes a downward drag on one side of the propeller disk. Such a device operates only by reducing thrust and does not produce a corresponding increase in thrust on the other side of the disk to keep the net thrust the same so it is not a particularly desirable type of control. Two types of roll control that have been suggested at times, but will not work satisfactorily, are the use of the engine exhaust for the case of a turboprop engine, or the use of a vane beneath the propeller. The exhaust of conventional turboprop engines, however, simply cannot produce enough thrust to give the required moment with a reasonable moment arm. A vane beneath the propeller such as that shown in Fig. 8 produces a very unsatisfactory motion because on an aerial jeep it cannot be very far below the center of gravity if the desirable low silhouette of the jeep is to be maintained. When such a control vane is fairly close to the center of gravity it produces a sideforce which is relatively large in proportion to the moment so that the resulting motion is of the type illustrated in Fig. 9. An application of the control for right roll, for example, causes a sideforce to the left which causes the machine to move to the left an appreciable amount before it banks enough for the tilt of the thrust vector to move it to the right. This type of motion may not look very bad since after a short time the bank angle becomes very large and the displacement in the conventional direction becomes very large in proportion to the initial movement. Free-flight model tests at the Langley Research Center in the past have shown, however, that for normal hovering flight in which the pilot is interested in correcting a small error in bank or banking slightly to move sideways slowly this initial movement in the wrong direction is very disconcerting and makes the motions of the vehicle appear erratic and jerky.

For a new type of vehicle such as the aerial jeep there is always the question of how much control is required. Helicopter experience might be used as a guide, but on a machine as unstable as the Langley two-shroud and four-shroud models the control requirement might be appreciably different from that of a helicopter. The free flight models are not generally used for accurate quantitative data, but in a new field such as this where there is no directly applicable precedent, the control requirements of the models might be a useful guide. The models shown in Figs. 5 and 6 were controlled by jet reaction controls at the side and rear of the model to give practically pure moments in order that the amount of control required could be ascertained without becoming involved in how the moment was to be obtained or the side effects of a particular type of control. In these tests it was found that the control should be capable of producing the following angular accelerations:

$$\text{pitch} = 2.0 \text{ radians/sec}^2$$

$$\text{roll} = 6.0 \text{ radians/sec}^2$$

$$\text{yaw} = 1.0 \text{ radians/sec}^2$$

With controls having these values of effectiveness it was possible for the pilot to control the models without artificial stabilization, or it was possible with appropriate equipment to stabilize the models. The above values of acceleration due to control deflection are the values at the model scale. For a full-scale aerial jeep of the size currently proposed, about 10 feet wide and weighing about 2,000 pounds, the accelerations would scale to about 30% of these values.

STABILITY IN FORWARD FLIGHT

Two of the predominant characteristics of the aerial jeep in forward flight might more properly be termed trim problems than stability problems; but they result from excessive speed stability, particularly in the case of the shrouded propeller configurations.

One of these problems results from the high drag of the shrouded propeller in forward flight which was brought out earlier using Fig. 2 as an illustration. Because of this high drag it is necessary to tilt the shroud forward to a relatively large angle to establish a balance of the fore and aft forces in forward flight as illustrated in Fig. 10. A rough rule-of-thumb for the case of the 10-foot-wide, 2,000-pound aerial jeep configurations with which we are presently concerned is that the shroud must be tilted about one degree for each mile per hour forward speed. The unshrouded propeller on the other hand does not have to be tilted nearly so far. A readily recognizable example of this fact is the helicopter rotor, which has to be tilted only a few degrees to produce a relatively high forward speed. The difference, as pointed out earlier, results from the fact that the shroud, which prevents slipstream contraction through the propeller, also tends to turn the air to align the exit flow with the shaft axis whereas the unshrouded propeller turns the incoming air through a much smaller angle and does not take out nearly as such of the forward momentum of the incoming air. The unshrouded propeller therefore does not have to be tilted to nearly so large an angle to establish an equilibrium of forces, as illustrated in Fig. 10.

It is evident that the use of suitable turning vanes beneath the shrouded propeller would make it possible to turn the slipstream backward as illustrated in Fig. 11 to produce a forward force on the vanes to offset the drag of the shrouded propeller itself. In this way it would be possible to achieve the forward speeds required of the aerial jeep without excessive forward tilt of the machine. There is practically no information available at the Langley Research Center on how extensive a system of vanes would be required, but it is understood that several manufacturers have investigated this scheme and have obtained some quantitative data. It is evident, however, that the vanes would have to be movable, probably with variable camber, to permit a straight downward flow without excessive losses in hovering flight.

Another solution to this problem of excessive tilt angles required for high speeds would be to depart from the concept of shrouded propellers fixed with respect to the airframe and to tilt the shrouds for the forward flight condition.

A second forward flight problem, which is more a trim problem than a stability problem is the large nose-up pitching moment developed in forward flight. This problem, which was introduced earlier in connection with Fig. 2, is especially severe for the shrouded propeller. If propellers are used in tandem there is an additional increment of pitching moment which results from the downwash of the front propeller on the rear one as pointed out previously in connection with Fig. 4. The use of turning vanes beneath the shroud as illustrated in Fig. 11 to permit forward flight without excessive tilt, which was suggested previously, would aggravate the nose-up pitching-moment problem since the forward force on the turning vanes acting beneath the center of gravity produces a nose-up pitching moment. One possibility for using the turning vanes without developing any additional nose-up pitching moment might be to use the vanes only on the forward shroud so that the downward lift of the vanes would provide a compensating nose-down pitching moment.

A third forward flight problem is an unstable variation of pitching moment with angle of attack which results from the fact that the center of gravity must be on the center of thrust for efficiency in the hovering condition but the center of thrust due to angle of attack in forward flight is markedly ahead of this point. This is true of a single propeller because of the characteristics of the propeller itself and is even more true of tandem propellers where the downwash of the front propeller on the rear one provides an added increment of instability by making the increase of thrust with angle of attack of the rear propeller less than that of the front one.

The three foregoing problems are all static stability and trim problems. A dynamic stability problem has been brought out by the very limited forward flight tests made at the Langley Research Center on the two-shroud tandem configuration shown in Fig. 5. The unstable rolling oscillation, which was evident in hovering flight, became more unstable as the forward speed was increased. This increase in instability was evidenced by the fact that as the airspeed was increased the model became unstable with the same amount of artificial damping in roll which had made the model stable in hovering flight. It was possible, however, to make the lateral oscillation stable again by increasing the artificial damping. The increase in oscillatory instability with increasing speed has not been analyzed in detail but it is evident that the model had all the major factors which are known to produce lateral oscillatory instability in an airplane. These factors are a high dihedral effect (large rolling moment due to sideslip), low or negative directional stability, high radii of gyration, and a nose-down inclination of the principal axis of inertia.

CONTROL IN FORWARD FLIGHT

In general, it seems that any lateral (roll and yaw) control system suitable for hovering flight will also be satisfactory in forward flight. The forward flight condition, however, imposes additional requirements on the longitudinal control system in that it must be capable of trimming the large nose-up pitching momemt encountered in forward flight.

Because of this requirement for a large pitching moment for the forward flight case the use of propellers in tandem seems very attractive because it is possible to produce very large pitching moments by increasing the thrust of the rear propeller and reducing the thrust of the front propeller. Other control systems might be devised however, such as cyclic pitch control or spoilers which reduce the thrust of the forward part of the propeller disk and thereby eliminate the nose-up pitching moment.

In any of these cases, however, this large change in trim, at least for shrouded propeller configurations, may make it difficult to provide enough control to trim out the nose-up pitching moment with a single control stick without having excessive control sensitivity for hovering, or maneuvering in forward flight. In this case it might be necessary to provide a separate control for establishing the gross control moment while the normal control stick serves as a vernier control for maneuvering the aircraft.

The use of any system such as turning vanes beneath the shroud to obtain a forward flight condition without excessive forward tilt of the machine would seem to be subject to the same criticism in that a separate control would have to be provided to establish the gross forward speed condition while the conventional control stick would provide the vernier control by tilting the machine. For example, if a machine was in high-speed forward flight and the pilot suddenly wanted to stop to avoid some obstacle or avoid revealing himself, he could not do so by pulling back on the control stick and adjusting the throttle setting to maintain altitude. He would also have to operate a third control. Since all his hands and feet would be otherwise occupied, this additional control would probably have to be a thumb switch on the top of the stick which is at best a clumsy, coarse control. This difficulty might be avoided by appropriate design features. For example, if turning vanes were used beneath only the forward shroud they might reduce the pitching moments in forward flight and reduce the tendency toward an overly sensitive pitch control and the need for the separate trim device pointed out in the previous paragraph. The turning vanes might then be linked to move in conjunction with the pitch control so that the forward stick movement required to produce the pitching moment for forward flight would also provide the required vane deflection. In such a case it might be desirable to have nonlinear variation of vane deflection with stick deflection so that the stick movements near center required for ordinary hovering flight would not cause excessive linear accelerations because of the vane deflection. There is not sufficient data available to properly evaluate such a system at the present time, but all of the various trends brought out are all in the proper direction.

Experience with the two-shroud flying model of Fig. 5 has shown that the model was not appreciably more difficult to control in forward flight than in hovering in spite of the angle-of-attack instability previously mentioned. It was possible to control the model in both pitch and yaw without the use of artificial stabilization. This result is not intended to imply that the behavior of the model was satisfactory for flight without artificial stabilization as the normal condition. The behavior was satisfactory, however, for an emergency condition in the event of failure of an artificial stabilization system. Control of the model in roll was not satisfactory without a high degree of artificial damping in roll as evidenced by the fact that as the speed increased the pilot became unable to control the unstable rolling oscillation, even with a moderate degree of artificial damping.

CONCLUSIONS

It can be concluded from the experimental work that has already been done and from analysis that the aerial jeep is feasible from a stability and control standpoint. It can be made to fly satisfactorily in both hovering and forward flight, although it may require a certain degree of artificial stabilization with simple straightforward and well-understood artificial stabilization devices to achieve satisfactory stability. It should also be possible to achieve the maximum forward flight speeds required with a reasonable aircraft attitude for either shrouded or unshrouded propeller configurations, although a certain degree of mechanical complication will probably be required to do so with shrouded propeller configurations. A great deal of research and development on the many detailed problems brought out in this discussion is required before entirely satisfactory solutions to all the problems can be discovered and proven.

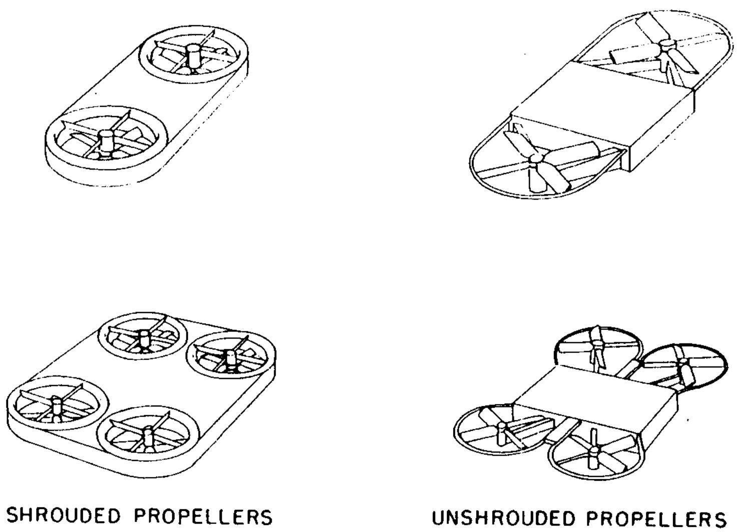

Figure 1.- Generalized aerial jeep configurations. NASA

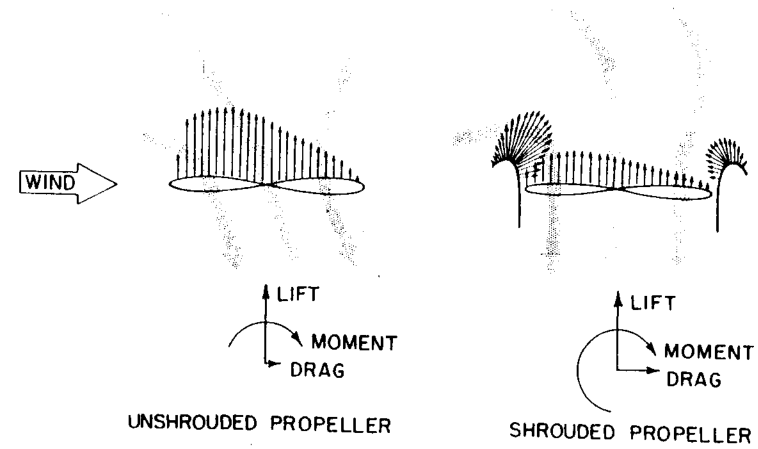

Figure 2.- Characteristics of shrouded and unshrouded propellers in a sidewind. NASA

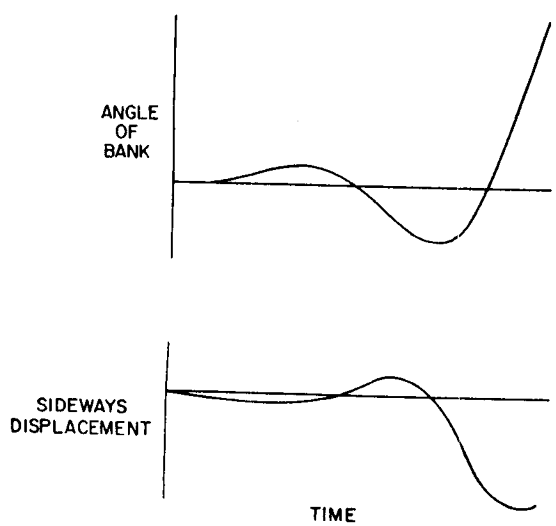

Figure 3.- Example of pitching or rolling oscillation of aerial jeep. NASA

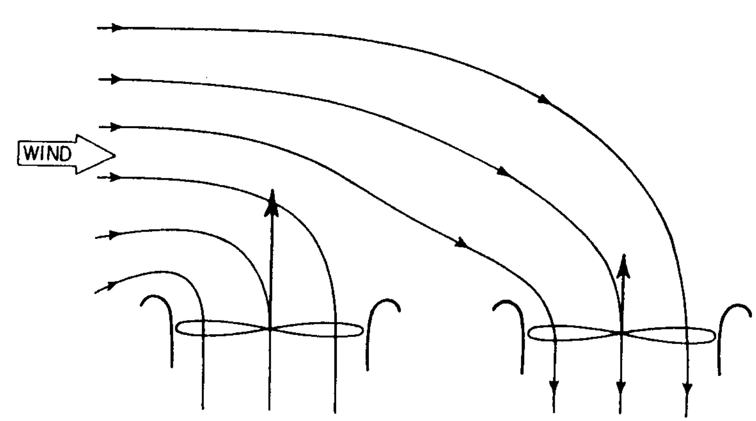

Figure 4.- Effect of downwash on thrust of propellers in tandem. NASA

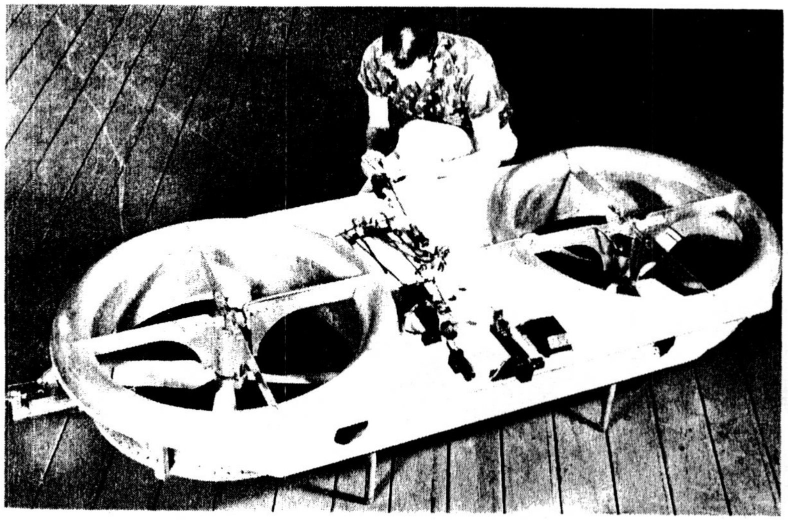

Figure 5.- Two-shroud flying model. NASA L-58-2176

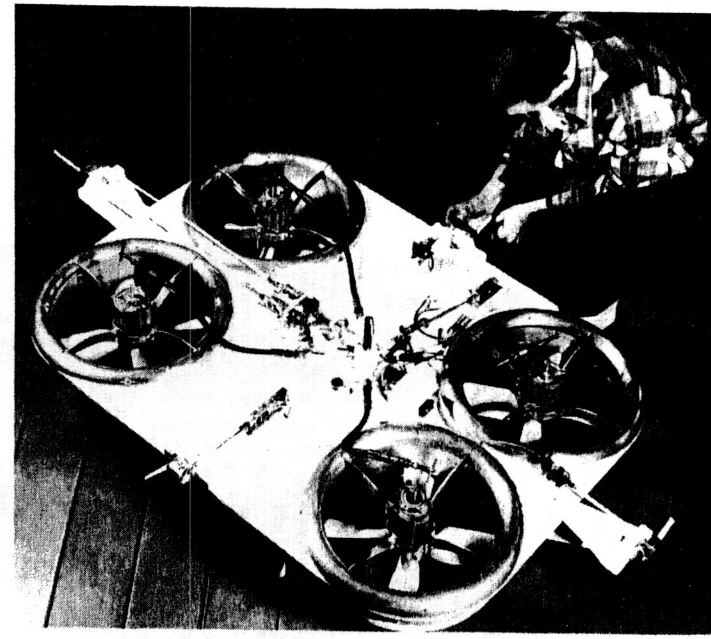

Figure 6.- Four-shroud flying model. NASA L-58-432.a

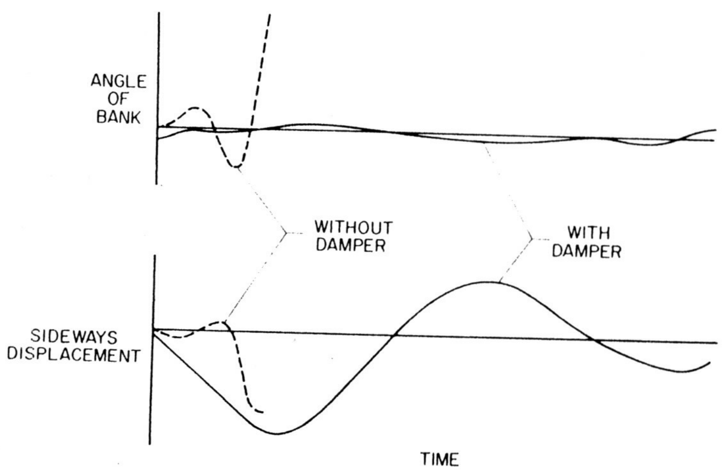

Figure 7.- Effect of artificial damping on rolling oscillation of four-shroud flying model. NASA

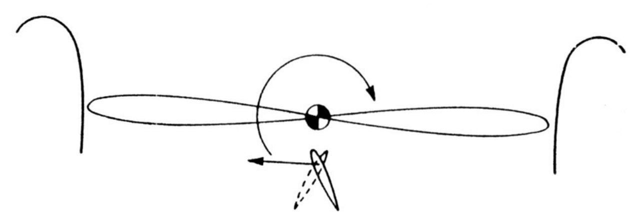

Figure 8.- Pitch or roll control vane. NASA

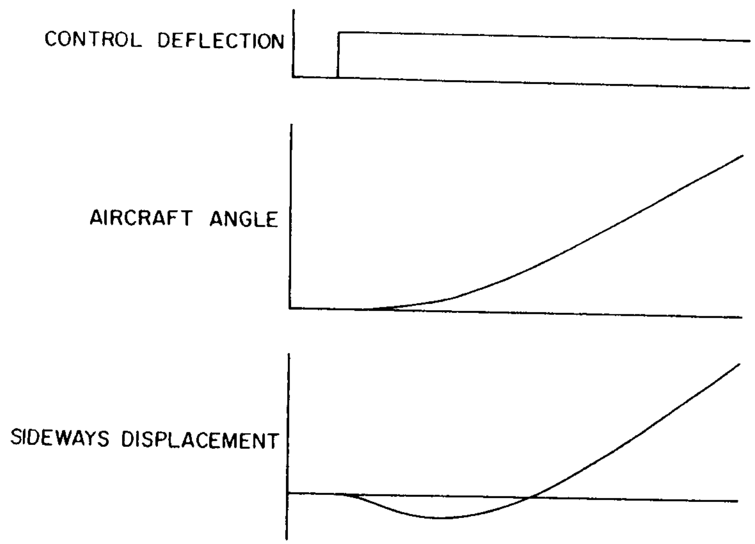

Figure 9.- Motion resulting from use of control vane below shroud. NASA

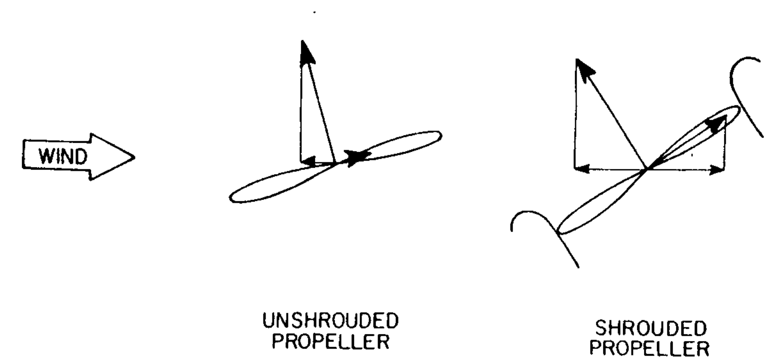

Figure 10.- Tilt angle required for forward flight. NASA

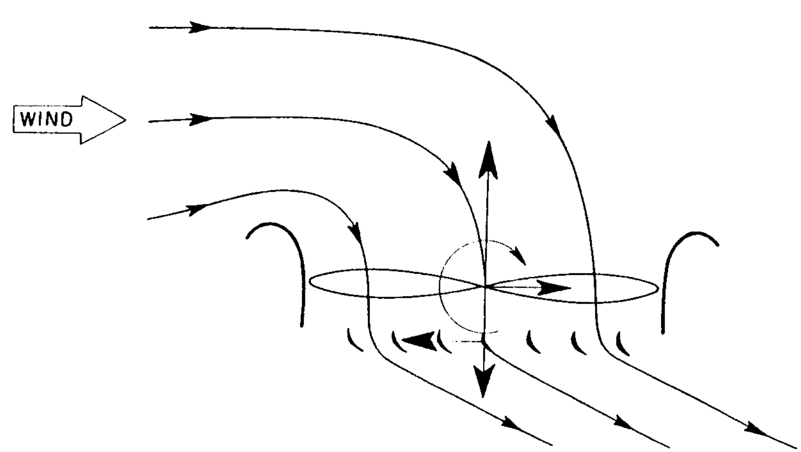

Figure 11.- Turning vanes beneath shroud for forward flight. NASA